SEISMIC REGIONALIZATION, SIGNAL DETECTOR AND SOURCE LOCATOR

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ABSTRACT

This class of problems represents a permanent challenge to seismologists despite much ingenuity and efforts over the last decades. The persistent epicenter location problem is illustrative; now as in the 1960 a main research strategy for improved accuracy is tied to an elaborate system of P- and S- travel time and station corrections. For local ranges results would hardly be optimum since the major problem here is that of proper identifying S-phases in largely "chaotic" recordings besides ignoring the information potential in the waveforms themselves. In the simplifying case of spatially stationary signals from a specific mine or quarry it has been demonstrated previously by Fedorenko et al. (1998, 1999) that exploiting waveform information from a network of stations or a single 3-comp. station result in enhanced epicenter locations and source type identification. Corresponding analysis in case of earthquake waveforms are more complex since source type and locations are not necessarily spatially stationary; in essence earthquake records are "deformed" as a function of epicenter distance. The first problem encountered was surprisingly lack of adequate data; for detector research long time intervals are needed while for location station spacing should for a start be between say 15 to 60 km. Instead of wasting much time on local network records, often of poor quality, we deployed our own seismograph network using geophones as seismometers and preamplifier and A/D-converter of our design. Also, our 3-component instrument was tested through joint operation and site sharing with a Kinemetrics Ranger station — not clear which instrument had the best performance. Data transfer often proves to be ruinous in local network operation but not so for us; we simply launched a "school" project with sensor installations in school yards including access to the school's Internet so free data transfer to server in our office. An additional benefit is access to the Internet Time Servers with timing accuracy around 25 msec. Currently 5 stations are operational and 10 more schools scheduled for installation in the Fall of 2001. Firstly, we were somewhat hesitant to start research here since the widely used STA/LTA detector is simple, efficient and robust. However, the long seismic noise records now at hand showed that waveforms and also their envelopes are uncorrelated between components. Exploiting this feature, we designed a 2D-detector jointly incorporating detection statistics both from horizontal and vertical components. 3 filter bands; 1.56 - 3.12, 3.12 - 6.25, and 6.25 - 12.5 Hz were selected from wavelet transform considerations. The 2D-detector is superior to the 1D STA/LTA detector; operating on a RMS threshold level of 3 and still no "noise" triggering. More than 100 detections daily but most of these are traffic "pulses", very local explosions and so on. Detector output, also placed on Internet, is RMS and duration of detection state for the 3 filter bands so we have a "finger feel" of ongoing seismic activity. Since network aperture now is about 35 km we will soon have an event listing and epicenter locations on Internet in order to stimulate science interest among students and future seismologists. Inversion of BB records from large earthquakes is an efficient tool in analysis of source mechanisms including focal parameters. For small events at local distances we are faced with complex and unpredictable waveforms from which mainly P- and S-arrival times are extracted and subsequently used for epicenter determinations. We aim for using waveform envelopes obtained through Hilbert transform for epicenter refinements. First step is to use Lg envelope peaks which are easily pickable and besides have a very consistent (group) velocity of 3.5 km/sec +/- 0.1. The main challenge is that of "'deforming" envelope records in such a manner that we can "predict" them 10 - 30 km away from a given reference station and reference events. In principle, this approach should give excellent results if successful simply because we use dynamic wavefield information for location as compared to conventional kinematic phase information as now.

KEY WORDS: seismograph design, school project, waveform envelope, 2D detector, deformable templates, event location

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OBJECTIVE

Progress in seismology is tied to 2 specific factors, namely i) easy access to digital network data of high quality and ii) ensure a continuous influx of talented students to our science for at least maintaining current research activities. These challenges are not particular new and a recent approach of growing popularity is that of launching various kind of seismic school projects as proposed in Husebye and Thorensen (1984). The rational is obvious; earthquakes are a manifestation of the dynamic Earth and as such easily catch the attention and imagination of many high school students at least for the few days such disasters are given media exposure. To capitalize on this albeit short lived interest in natural phenomenon we think that students should become active partners in seismic monitoring that is operate their own school specific 3-component seismograph stations, undertake analyst tasks and also become partners in special research ventures. Ideas and enthusiasm are not enough for launching successful school projects as is clear from many such undertakings. Failures appear to be associated with lack of high-sensitive and inexpensive instrumentation in combination with clumsy data access and lack of interactive analysis software for students. Although educational projects are noble, our launching of a school project in Norway (http://www2.ifjf.uib.no/SEIS-SCHOOL) was and is mainly motivated by a need for high quality data for CTBT research at local and regional distance ranges as shown in Fedorenko et al. (2000). In our experience it is not unproblematic to find small network data of high quality for apertures of 50 - 100 km for which local recordings are easily retrievable. After much efforts with scant success in obtaining data from established international and national data centers we decided to investigate whether we could deploy our own network of inexpensive, high quality stations with a minimum of running costs. As to be demonstrated below, we have been successful in this undertaking (Fig. 1) albeit time and work invested in this enterprise exceeded our initial effort estimate.

RESEARCH ACCOMPLISHED

Instrumentation

A single seismometer costs at least $ 2000 so we looked for cheap geophones (approximately $ 60.) as a substitute. In this way 3-component station may become affordable also for groupings outside the established network operators. However, stations need preamplifiers so we designed our own in order to reshape the original geophone velocity response to a flat acceleration response in the range 0.45 - 45 Hz - symmetric around geophone eigenfrequency at 4.5 Hz. The advantage with a flat acceleration response is that the noise is approximately white above 1 Hz while velocity instruments have response noise fall-off roughly as $1/\omega$. It is also convenient for denoising of seismic records using wavelet transform operations as shown in Fedorenko and Husebye (1999a). The A/D-converter (also own design) has an effective dynamic range of 19 bits achieved through gross oversampling and at a cost of $ 350. Like the preamplifier it is cheaper than those commercial available. Timing; 3 venues are available namely i) radio clock ($ 50.), ii) GPS ($ 300.) and iii) Internet clock (free). For school installations with free Internet connection the latter is preferable as precision is always better than 25 msec. Station sensitivity: The simplest one was that of site-sharing with nearby station ASK (Kinemtrics Ranger) having velocity response. Records are not as expected identical but all local events recorded by ASK was also recorded by our "geophone" station. Since sensitivity depends on pendulum mass there is no point in trying to extend small mass geophones to record the relatively low frequency part of earthquake signal spectra. Station sensitivity also depends on internal and external noise fields. The theoretical investigation here indicates that the sensor internal noise is more than 6 db below the ambient noise at the ARCESS array central site (Z-component) within the 0.25 - 10 Hz band as demonstrated by Fedorenko (2001). The sensor noise model includes voltage and current noise sources at both inverting and non-inverting inputs of OPA2227 operational amplifier, suspension and thermal (Johnson) noise of geophone and also the thermal noise of resistors connected to OPA2227 inputs. For GS11D 4.5 Hz geophones from GeoSpace Corp., Houston, thermal noise dominates being approximately twice larger than the operational amplifier noise. In this case the use of dual geophone sensors will improve SNR by 6 dB. Suspension noise is negligible. Sensors with flat acceleration responses have SNR better than 6 dB (2.0 in r.m.s amplitude) within 0.2-10 Hz band relative to ARCESS noise model as shown in Fig. 2. In other words, our "geophone" instruments may conveniently substitute conventional S-13 seismometer in areas with moderate seismic noise levels, such as Norway.

Signal Detection

Our initial motivation for developing our school station was not 'school' but the need for long strings of high quality records for detector experiments as shown in Fedorenko and Husebye (1999b). Besides, some of the local (national) stations were exceptional spiky. Outcome of these efforts are an anti-spike filter incorporated in the preamplifier design and that our new very efficient 2D-detector operates in the 3 frequency bands 1.563-3.125, 3.125-6.25 and 6.25-12.5 Hz. Also, for better envelope shapes we use a pulse optimal filters which appear to give sharper onsets than frequency optimal filters. The 2D-detector is of the familiar STA/LTA-type but taking advantage of uncorrelated noise between Z- and H- components both for conventional and envelope waveforms as shown by Fedorenko and Husebye (1999b) and Husebye and Fedorenko (2000). A rough distance estimate is obtained through an angle of incident estimate for presumed P- onsets. Operational experiences so far indicate that no false alarms occur even at low threshold levels at 3.0. For ease and school instructions the detection logs are on Internet not lagging behind more than a few minutes relative to arrival time (http://pcg1.ifjf.uib.no). Likewise, with a few additional clicks the corresponding record segments of Z-component are displayed in the 3 filter bands of the 2D signal detector (Fig. 3). Further refinements are under consideration and implementation; as shown by Fedorenko et al. (2000) a few additional clicks would activate the PITSA signal analysis package by Scherbaum and Johnson (1992) for phase pickings, polarization analysis and epicenter locations using grid search techniques. These flexible seismogram and signal analysis options will presumably also be instructive for professional seismologists who often are not quite familiar with observational seismogram analysis. Also, it should not be forgotten that much creative research is aimed at explaining unexplained wavefield features.

Data Transfer and Running Costs

Our interest in school cooperation is partly motivated by access to the permanent school Internet and in this way eliminated an often painful aspect of network operations namely high data transmission costs. Our set up is that of installing the data logger in the respective schools and then transfer data to the network server in our office at the University. In turn, schools download their own and other station data from the server and also application software. So far only the PITSA analysis package is available for data analysis which in near future would be "coupled" to a grid search routine for epicenter location of local events. Presently, data and detector log access and flexible software routines are of highest priorities in our school project. We hope that student teams would undertake routine analysis of local events.

Seis-School Organization

We started simply by installing our prototype sensor in the school yard of Aasane Gymnasium (ASAS) just around 15 km away from the University of Bergen campus. High school student interest was triggered with a local earthquake occurring a few weeks later some 35 km west of Bergen. With good exposure of students and their ASAS recording in local newspapers our school project got a flying start. In another school, Sotra, located in the area with strong shaking from the above local earthquake, a group of students undertook a macroseismic investigation of this event and their findings were rewarded with a prize in a national Young Scientist contest. As of today, 4 schools have seismograph installations while 10 more are waiting for deployments (see Fig. 1). In each school special student teams are (will be) formed who will be partners in appropriate "young scientists" projects and local seismicity monitoring.

School Stations and CTBT

The educational aspects of school projects are noble but reality necessitates that such records are of professional quality. In our case, the original design strategy aimed at data for pure research that is for signal detection and event location experiments. The school "association" becomes very attractive in terms of enthusiastic students and free Internet access equivalent to an elimination of operational costs. The obvious penalty here is that site selection is restricted and hence not optimum in most cases. In other words, how good is our 3-comp. school seismographs and what is their usefulness in CTBT monitoring? As mentioned, a first simple test was site-sharing with a 3-comp. Kinemetrics Ranger station of the national (Norwegian) seismograph network. The outcome here for local events was that the respective event

detection performances were roughly similar or school station slightly better. Since both responses and detectors are different it is difficult to quantify in detail the respective performances of these 2 stations. As part of our station performance evaluation a rigid study of internal instrumentation noise in the preamplifier and geophone and in the A/D-converter has been undertaken. The preliminary outcome of this study (Fedorenko, 2001) is that the internal RMS noise level appears to be a factor of 2.2 less than the ambient ARCESS center sensor (Z-comp.) noise level. In other words, our school station is capable of detecting real seismic signals in the ambient noise as illustrated in Fig. 2. By necessity, the CTBTO monitoring seismic network (IMS) is teleseismic in view of the relatively limited number of arrays and stations deployed. For events of small to intermediate magnitudes the corresponding number of reporting stations will be few - often only 5 or less. To overcome such a drawback there is a provision for extracting data from so called auxiliary stations for improving event locations; travel time corrections for these stations are also in the CTBTO data base. So what about school stations of the type developed by us and described here ? Data quality is no objection (e.g., see record display in Fig. 3,4) and besides timeliness of availability do not pose any hindrance. In our set-up the data are sent server within a minute of end of detection state and then immediately accessible via Internet. Extensive timing corrections are not needed for a simple and effective check of a trial epicenter solution; at local distances an envelope peak should correspond to the universal Lg group velocity of 3.5 +/- 0.1 km/sec as shown by Husebye et al. (1998). In this way location errors exceeding 10 - 12 km are easily detectable.

Deformable Templates — a New Approach to Event Location

Accuracy and robustness in epicenter locations is an outstanding problem in CTBT monitoring. It is complex in the sense that it depends on network configuration relative event location, adequacy of local travel time curves and the analyst's ability to properly identify secondary S-phase onsets. In particular, for small events with few reporting stations relatively large location errors may occur. Currently, an intrinsic time correction scheme is under implementation in the CTBT system for improving epicenter locations tied to alpha and beta stations and arrays. Drawbacks with such a "correction" scheme is complexity in particular as no fixed reference system is available; station correction may be magnitude dependent that is number of reporting stations used is not fixed and that referenced travel time tables are being regionalized. In our opinion, the foremost drawback here is that too little information is extracted from the records - just some kinematic phase arrival times. The local high frequency records are complex so pickings of secondary S-arrivals are often problematic and occasionally error prone. We have previously demonstrated that using waveform envelopes from Hilbert transform operations from a few stations suffice for very accurate locations of stationary and repetitive sources like mining explosions and quarry blasts as shown in Fedorenko et al. (1998; 1999). Other waveform approaches are using optimization techniques for relative accurate pickings of phase times (variant of the JED-scheme) in aftershock sequences, waveform synthetics and so forth. Instructive results have been obtained but techniques are not easily transportable nor flexible for areas with dispersed earthquake activities. The basic problem in waveform location analysis is that we must be able to predict waveform changes as a function of differential epicenter distances; for stationary mining explosions this basic problems are non-existent. Since the high frequency parts of local seismogram appear chaotic and hence unpredictable in contrast to the corresponding envelopes which vary far more smoothly. Also, synthetics are unable to reproduce real local seismograms unless 3D crustal models are used as shown by Hestholm et al. (1994) and Hestholm (1999). With our school network records we have a good data base for waveform location research. As demonstrated in Fig. 4 the original waveforms change fast between the school network station while vary slowly in case of the corresponding waveform envelopes. As shown in Fedorenko and Husebye (1999a), in such case a conventional phase picking may be reduced to nonlinear optimization problem in a 9-dimensional space in which the parameters which minimize the difference between model and observed envelops are sought. The joint use of seismic network data increases number of parameters dramatically. Nonlinear optimization in high dimensional space using standard methods is possible but slow thus being a primary limiting factor for its usage. However, the model and observed envelopes are topologically similar which allows us to develop fast optimization algorithms based on a deformable templates technique. The latter proves to be very useful in pattern recognition problems. As shown in Jain and Zongker (1997), a deformable template approach has recognition rates of the handwritten characters up to 99.25% on a 2000 character subset. This approach can be directly applied to the sequence of envelops from dense seismic networks. Cootes et al. (2000) demonstrate the way to represent an object as complex as a human face by a small number of models.

Basics of shape modeling are shown in Zhu (1999). The essence of our analyzing strategy based on deformable templates methods is:

- Build a set of skeletonized models representing the shape of envelops of seismic events on local distances.
- Develop the method to fit observed envelops to models using a suitable deformable templates algorithm.
- Choose the classifier appropriate for our problem using data from our Seis-School network.
- Develop an epicenter location algorithm using the envelope deformations along time axes from deformable templates methods.

So far, records from our school network have proved both beneficial and very effective in selecting events for our ongoing methodical approach of applying deformable templates techniques for a different methods of seismic event location.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions: Main research efforts have been focused on instrument development, network deployment and operation. Four 3-component stations are now operative in local school yards and event record segments are automatically transmitted via Internet to server in our offices in University of Bergen. Instrument sensitivity using inexpensive 4.5 Hz geophones is good and record quality suffice for CTBTO oriented research problems. School deployments give direct and free Internet connection so operational costs are zero. User access to records are simple and efficient; detection logs are retrieval from Internet including options for PC screen visualization. Password is currently required for extracting data files for further record manipulations. These network recordings have been used for developing a new 2D signal detector and its practical testing over many months of station operations. The 2D detector combines RMS powers on both H- and Z-components permitting an STA/LTA equivalent threshold of only 3 without false alarms (or noise detections). Besides arrival time and signal power estimates the detector also extract rough azimuth and angle of incident estimates. Glitches and other type of record disturbances are not entirely uncommon in station operations; such nuisances are removed by an anti-spike filter incorporated in the preamplifier of our own design. The cost of a complete 3-component instrument based on 4.5 Hz geophones as sensors, exclusive work, amounts to less than US $ 1000. In comparison, a single seismometer of conventional design (like Kinematrics Ranger or S-13) has a price tag exceeding $ 2000.

Currently, the CTBTO epicenter location approach is tied to an intrinsic set of travel time and station corrections. For local events we are considering a deformable template approach using envelope traces (Hilbert transforms) from our school network. The rational here is that waveforms are more informative than kinematic time corrections and also that envelope shapes are slowly varying with distance re the original waveforms. Thus in principle we should be able to project spatially envelope records between network stations and in this way obtain enhanced epicenter accuracy - we are establishing a data base here from our own network.

Recommendations: CTBTO/IMS monitoring would be more efficient if more auxilary station recordings are used in analysis. We have demonstrated the feasibility of deploying and operating seismic networks where data quality is high and instrument and operational costs are low. Also, we have demonstrated that Internet may be used for almost instantaneous access to a wide class of network recordings. Furthermore, 2D detectors should be more widely used in view of their efficiencies in suppressing false alarms (noise triggers) and alternatives to travel time parameters for event locations should be more vigorously pursued.

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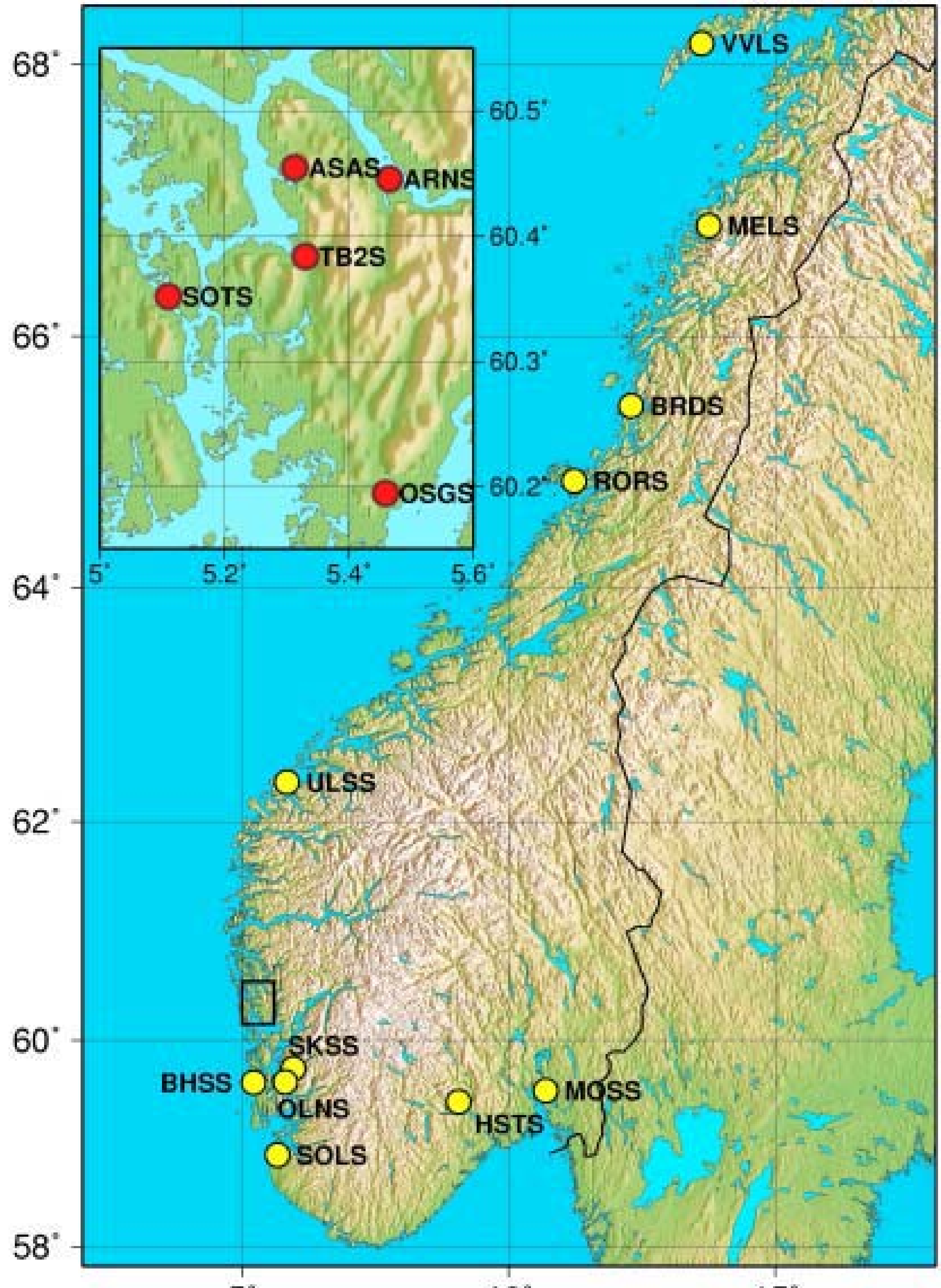

Figure 1. The school network in Norway; insert shows operative stations around Bergen (red dots) while yellow dots are participating school waiting for installation. The ASAS station has been in continuous operation since 1 Nov 2000.

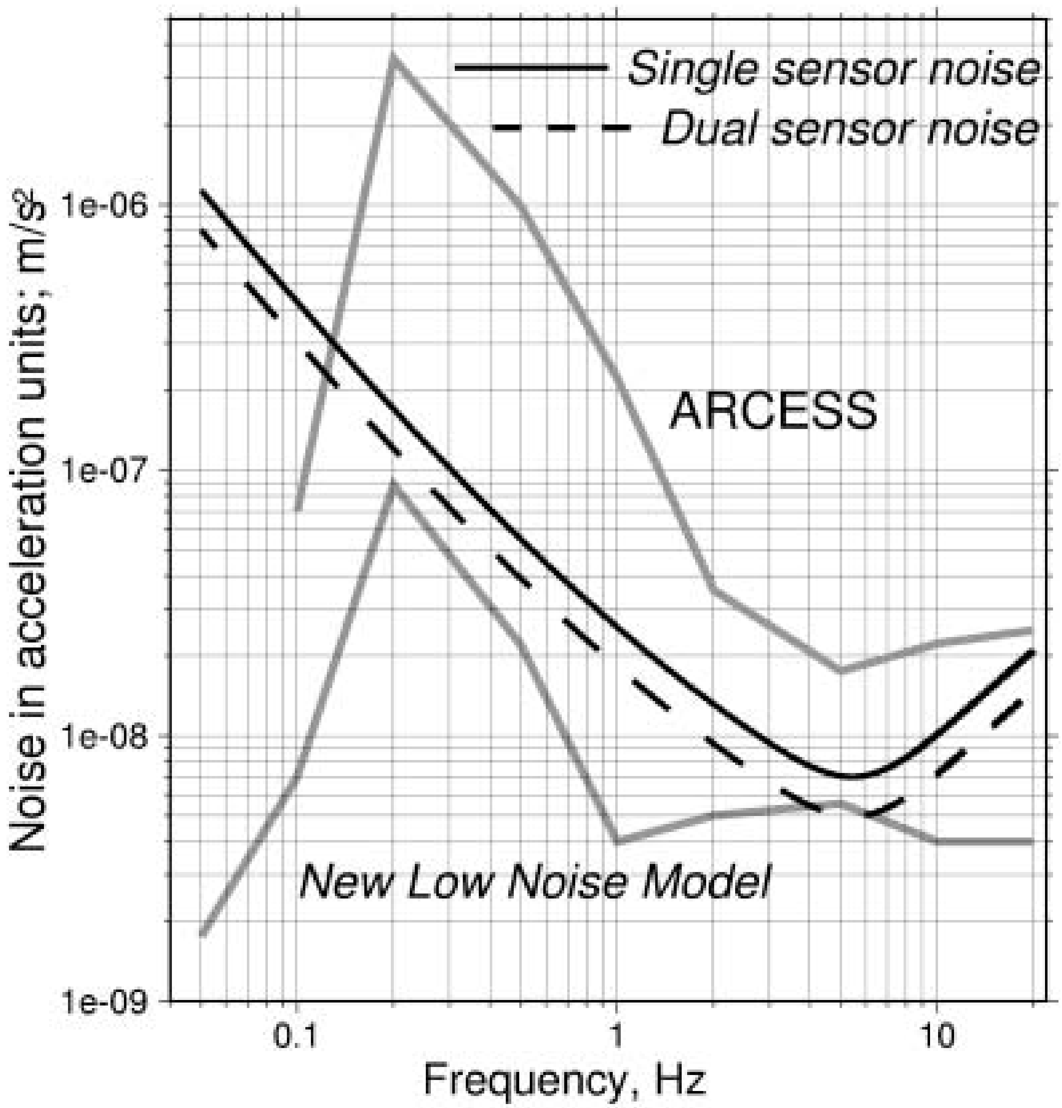

Figure 2. Geophone seismic sensor noise versus the US Geological Survey New Low Noise Model as shown in Peterson (1993) and ARCESS noise recalculated into acceleration r.m.s. units. Solid curve shows equivalent noise acceleration for current single-geophone design; dashed curve represents dual-geophone sensor.

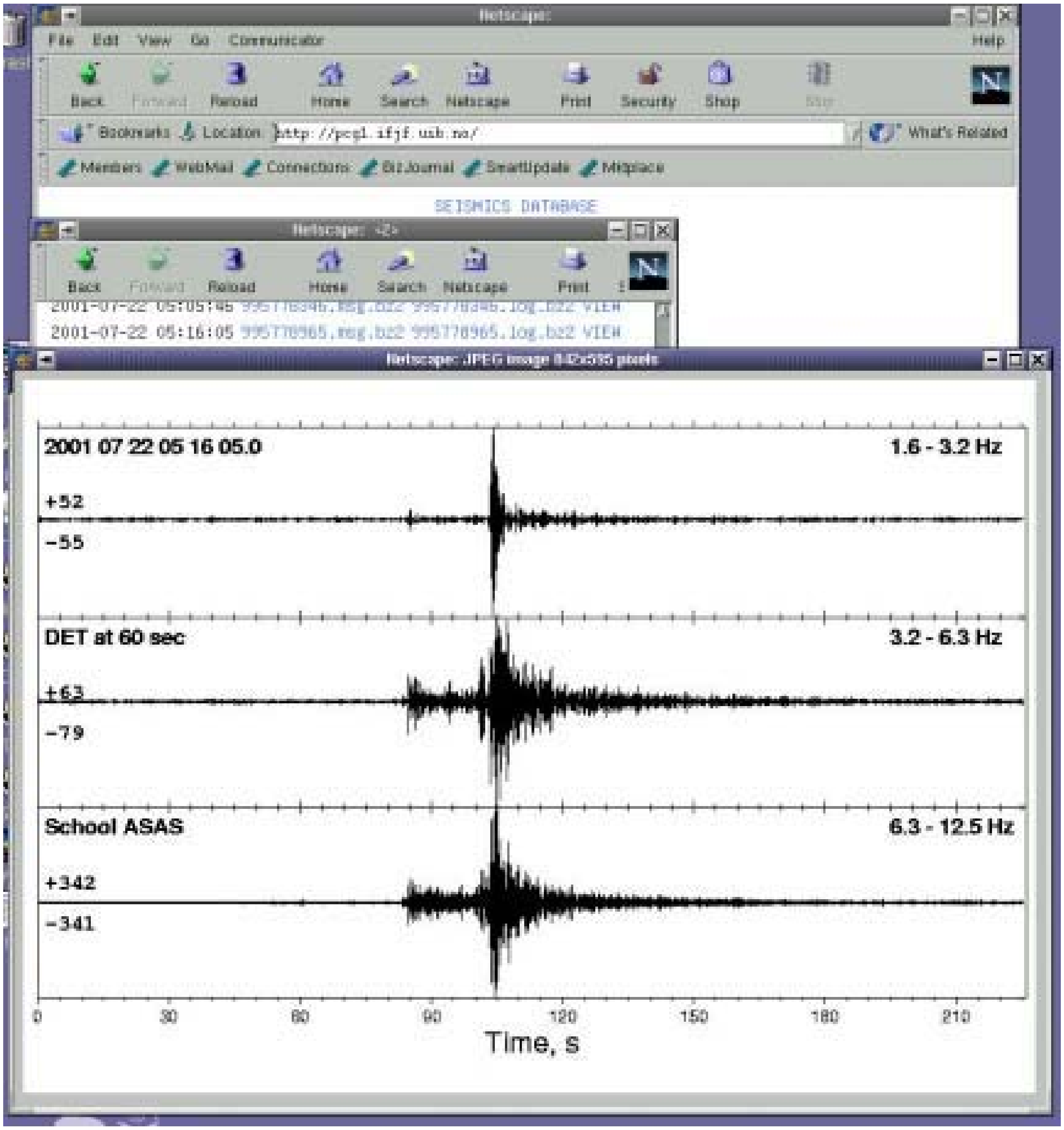

Figure 3. Viewing 'school station' recordings on Internet http://pcg1.ifjf.uib.no/ . The SEISMICS DATABASE appears and a click gives station choice - see insert in Fig. 1. A click then give options of date for viewing; Year/Month/Day. Then the daily detections with view options appear; a click here produce more than 200 seconds of Z-comp. traces in the respective 3 filter bands of the detector. In near future detection logs would also be available for individual stations and multistation detections which will facilitate event selections significantly for school participants. Our efficient 2D detector detects much of garbage signals of very local origin which will be automatically removed from log listings. Waveform data access requires password.

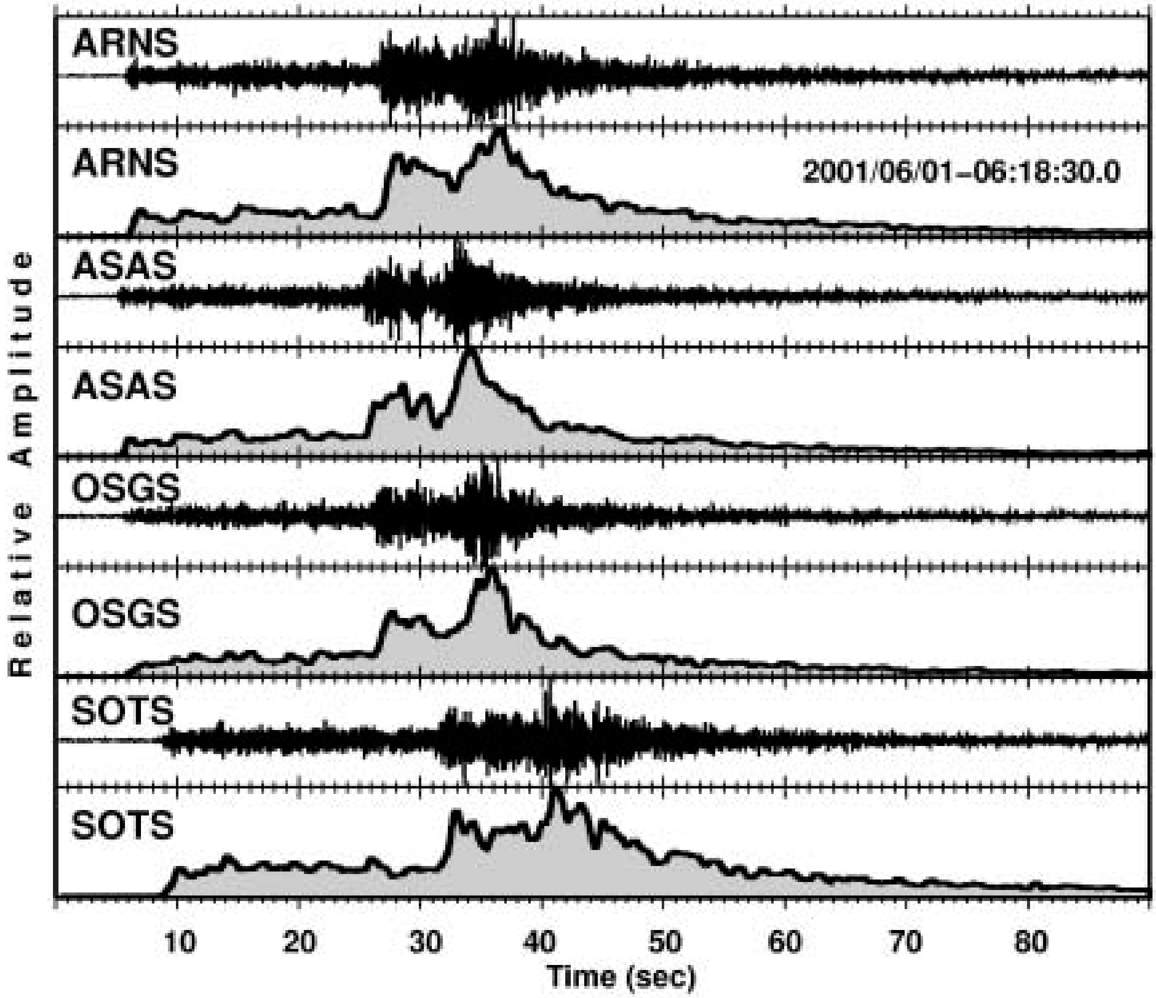

Figure 4. Records from the 4 school stations shown in Fig. 1 from an earthquake in Northern North Sea. Below individual station records are the corresponding envelopes. The outstanding feature here is the fast variation of the original waveforms between the network stations while envelops vary much slower. An essential element of the deformable templates technique is the ability to project the envelope trace of station X so it matches that of station Y. The case of stationary mining explosions is much simpler since spatial waveform projections are not an issue.